

Rebuttal to reviewer's comments

The only comments made by the reviewer that needed attention are editorial as per the marked up manuscript and information supplied from the Indico website, both of which are attached.

All editorial comments made by the reviewer as indicated in the marked up manuscript has been implemented in the revised manuscript.

Sincerely

Dr Kessie Govender.

Referee: To be corrected

submitted on *Thu 14 May 2020 at 09:04*

Comments

1. Please address reviewer comments on manuscript pdf.
2. Please ensure that manuscript complies with SAIP Conference Proceedings layout style. (Refer to Guidelines and Templates link on Indico).
3. Deadline: 1 June 2020.

Answers

Does the article that you are being asked to review match your expertise? (On scale, + for yes or agree): Neutral

Are there any potential conflicts of interest if you review this article? (+3 for yes / -3 for no): Neutral

A1 Scientific merit: Is the work scientifically rigorous and accurate? Is it appropriate for the proceedings?: Neutral

A2 Clarity: Are the ideas in the paper communicated clearly and legibly?: Neutral

A3 Context: Is there sufficient discussion of the background for this work and suitable referencing?: Neutral

B1 Originality: Is the work relevant and novel?: Neutral

B2 Motivation: Does the problem considered have a sound motivation? All papers should clearly demonstrate the scientific interest of the results: Neutral

C1 Title: Is it adequate and appropriate for the content of the article?: Neutral

C2 Abstract: Does it contain the essential information of the article? Is it complete?: Neutral

C3 Diagrams, figures, tables and captions: Are they essential and clear?: Neutral

C4 Text and mathematics: Are they brief but still clear? If you recommend shortening, please suggest (below at comments) what should be omitted: Neutral

C5 Conclusion: Does the paper contain a carefully written conclusion, summarising what has been learned and why it is interesting and useful?: Neutral

C6 References: Are the references in the correct format? Are all references mentioned in the text and cited chronologically?: Neutral

Content: To be corrected

submitted on *Mon 10 Feb 2020 at 14:14*

Comments

The paper describes the setup and some results of a magneto-optical trap for laser cooling of rubidium atoms. The setup as described seems sound, but I don't see any original research. If what is required is a good description of a scientific experimental system to investigate interesting physics, then this paper achieves that. **There are a number of corrections that need to be done before this paper is published. I do not see where my corrections should be submitted; I can send by email.**

Criteria Evaluation

Does the article that you are being asked to review match your expertise? (On scale, + for yes or agree): Strongly Disagree

Are there any potential conflicts of interest if you review this article? (+3 for yes / -3 for no): Strongly Disagree

A1 Scientific merit: Is the work scientifically rigorous and accurate? Is it appropriate for the proceedings?: Agree

A2 Clarity: Are the ideas in the paper communicated clearly and legibly?: Agree

A3 Context: Is there sufficient discussion of the background for this work and suitable referencing?: Weakly Agree

B1 Originality: Is the work relevant and novel?: Neutral

B2 Motivation: Does the problem considered have a sound motivation? All papers should clearly demonstrate the scientific interest of the results: Agree

C1 Title: Is it adequate and appropriate for the content of the article?: Strongly Agree

C2 Abstract: Does it contain the essential information of the article? Is it complete?: Strongly Agree

C3 Diagrams, figures, tables and captions: Are they essential and clear?: Agree

C4 Text and mathematics: Are they brief but still clear? If you recommend shortening, please suggest (below at comments) what should be omitted: Agree

C5 Conclusion: Does the paper contain a carefully written conclusion, summarising what has been learned and why it is interesting and useful?: Weakly Agree

C6 References: Are the references in the correct format? Are all references mentioned in the text and cited chronologically?: Strongly Agree

Construction and testing of a magneto-optical trap for laser cooling of rubidium atoms

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Abstract. We describe in this paper details of the design, development and testing of a device to cool and trap neutral Rubidium atoms. The system consists of an ultra high vacuum chamber having a number of view ports, plus vacuum pumps, piping, vacuum gauge and valves. Rubidium atoms stored in a getter material *are* released into the vacuum chamber by means of electrical heating. Three pairs of counter propagating laser beams, each pair positioned on opposite sides of the chamber along three orthogonal axes, are used for cooling of the atoms in the chamber. The cooled atoms are trapped using a pair of anti-Helmholtz magnetic coils positioned on either side of the vacuum chamber. Optical sensors such as CCD cameras and avalanche photo detectors for measuring the light emitted by the trapped atoms are used to estimate parameters of the trapped atom cloud. ✓

1. Introduction and background information

A quantum optics laboratory is currently being developed at the Cape Peninsula University of Technology by the Quantum Physics Research Group within the department of *Electrical Engineering*. The group is engaged in laser-atom interaction research, particularly the study of interaction of lasers with cold and ultra-cold atoms. ✓

Cold atoms are produced in a device called a magneto-optical trap (MOT)[1, 2]. Atoms that are used in these experiments are alkali atoms (Group I elements of the periodic table). These atoms have a closed shell configuration plus one unpaired electron. Rubidium and Cesium are more common candidates these days, as there are readily available laser sources in the form of diode lasers that could be used for cooling these atoms [3, 4].

In this paper we focus on the design, development and testing of the magneto-optical trap. This exercise requires constructions skills in electronic, mechanical and optical systems. The only other institutions that are involved in similar research are the University of KwaZulu-Natal who have reported preliminary findings in cooling ^{85}Rb and University of Stellenbosch who are conducting research into cold ions.

This paper is organised as follows. The basic theory of laser cooling and trapping is presented in Section 2. In Section 3 an overview of the design of the magneto-optical trap is described. The performance of the trap is given in Section 4. The summary and conclusion is given in Section 5.

in South Africa (?)

2. Theory of laser cooling and trapping

In this section we explain the basic principle of cooling atoms using laser beams and trapping them using magnetic fields.

2.1. Electronic structure of Rubidium

Rubidium has 37 electrons and lies in the first group of the periodic table. There are two naturally occurring isotopes, ^{85}Rb and ^{87}Rb with an abundance of 70% and 30%, respectively. There is one unpaired electron which exits in the 5S orbital. Although we have managed to cool both ^{85}Rb and ^{87}Rb , we will discuss laser cooling using ^{87}Rb . The ground state and first few excited states of ^{87}Rb is shown in Figure 1. This figure shows the fine and hyperfine splitting of the 5S and 5P orbitals relevant for laser cooling.

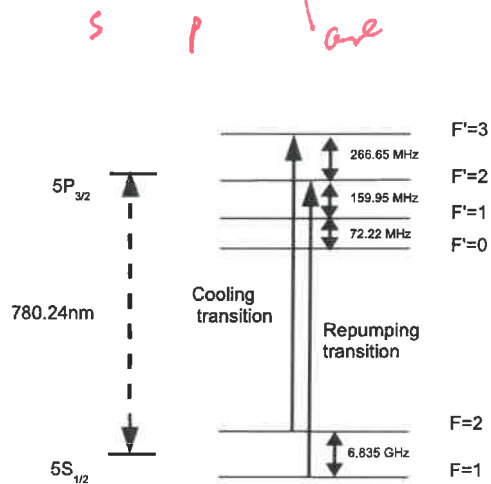


Figure 1. Electronic structure of ^{87}Rb .

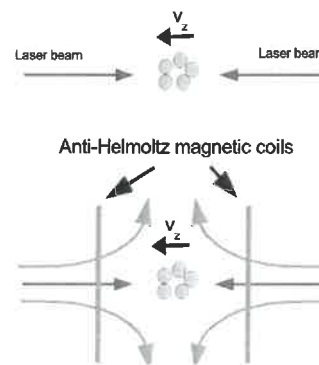


Figure 2. Laser cooling in 1D (top) and laser cooling and trapping arrangement (bottom). The vertical green bars represent anti-Helmholtz magnetic coils and the blue lines are the magnetic fields.

The transitions used for cooling are from $F=2$ to $F'=3$. For every thousand or so transitions the atom will decay to the lower ground state, thus taking it out of the cooling cycle. To bring atoms back into the cooling cycle a repumping laser is used to pump them to the upper F' state as shown in Figure 1. From there they have higher chance to decay to upper ground state.

2.2. Doppler cooling and trapping

We will illustrate laser cooling using a one dimensional situation as shown in Figure 2. A cloud of atoms are subjected to two counter propagating laser beams as shown. The laser frequencies are set to be slightly lower than the resonant transition of the atoms, i.e. the lasers are detuned with respect to the atomic transition.

Let's assume that the atoms are moving to the left with velocity v_z as shown. Atoms see the left approaching laser beam to have a higher frequency, due to a Doppler shift, closer to resonance and it is more likely to absorb photons from that beam. Energy and momentum are absorbed. With each photon absorption, the atom gets a momentum kick in the opposite direction thus slowing down the atom in the process. For the atoms moving to the left the right laser beam is further detuned (due to the Doppler shift) and the atoms are less likely to absorb photons coming from the right laser. The opposite happens for atoms moving to the right.

For speeds close to zero there is an inverse linear relation between the force F and speed v_z and it can be shown that [5]:

$$F = -\gamma v_z \quad (1)$$

where γ is a damping factor that depends on the decay rate of the excited state, mass of the atom, detuning of the cooling laser, Planck's constant and the wave number of the laser. The above equation represents a force that is similar to viscous damping. To achieve cooling in 3D, three counter propagating laser beams intersecting at right angles are used.

There is a lower temperature limit to which cooling can be achieved using Doppler cooling [2, 5]

$$T_{Dop}^{min} = \frac{\hbar\Gamma}{2k_B} \quad (2)$$

where Γ is decay rate of the excited state and k_B is the Boltzmann constant. For ^{87}Rb the above formula gives $T_{Dop}^{min} = 146 \mu\text{K}$. In practice, lower temperatures are achievable due to other mechanisms that come into play such polarization gradient cooling/Sisyphus cooling [2].

Although the lasers reduce the atomic velocities, they do not trap or change the density of the atomic cloud. Atoms can still drift out of the laser beam even when cooled. To achieve trapping, a pair of anti-Helmholtz coils (vertical green bars in Figure 2) are used to create a quadrupole magnetic field and the laser beams are left and right circularly polarized. The equation describing the force on the atoms due to the laser beam and the magnetic field is the same as for a damped harmonic oscillator. The atoms are thus attracted to both $v_z = 0$ in velocity space and $z = 0$ in physical space.

3. Overview of the magneto-optical trap

In this section we provide an overview of the vacuum system and optics for generating the laser beams for cooling. The schematic of the vacuum system is shown in Figure 3 and Figure 4 shows a simplified schematic of the optics for generating the cooling laser beams.

3.1. Vacuum system

The system consists of an octagonal vacuum chamber connected to three vacuum pumps, viz. ion, turbo and rotary pumps. The atoms are cooled in the octagonal vacuum chamber. Rubidium atoms stored in a getter material are released into the vacuum chamber by means of electrical heating. Three pairs of counter propagating laser beams, each pair positioned on opposite sides of the chamber along three orthogonal axes, are used for cooling the atoms in the chamber. These are shown as thick red arrows in Figure 3. The chamber has a number of view ports to allow for optical access. Three stages of pumping (i.e. rotary, turbo and ion pumping) are used to reduce the pressure from atmospheric down to approximately 10^{-10} mbar. The rotary pump is used first to reduce the vacuum pressure from atmospheric to around 10^{-3} mbar, the turbo pump is then switched on to reduce the pressure to around 10^{-8} mbar. Finally the ion pump is turned on to reduce the pressure to around 10^{-10} mbar.

When the system was first put together a bake out was done over a period of three days to get rid of residual gases stored in the walls of the system. The system was gradually heated to a temperature of 160 degrees C during the first day, kept constant at this temperature for the second day and gradually reduced from 160 degrees C to ambient on the last day. Only the rotary and turbo pumps were used during the bake out period. The ion pump was only turned on, on the last day of bake out when the system temperature was below 80 degrees C.

3.2. Optical system

A single laser is used to generate the three pairs of counter propagating beams needed for cooling. The major portion of the beam that emerges from the frequency stabilization set up

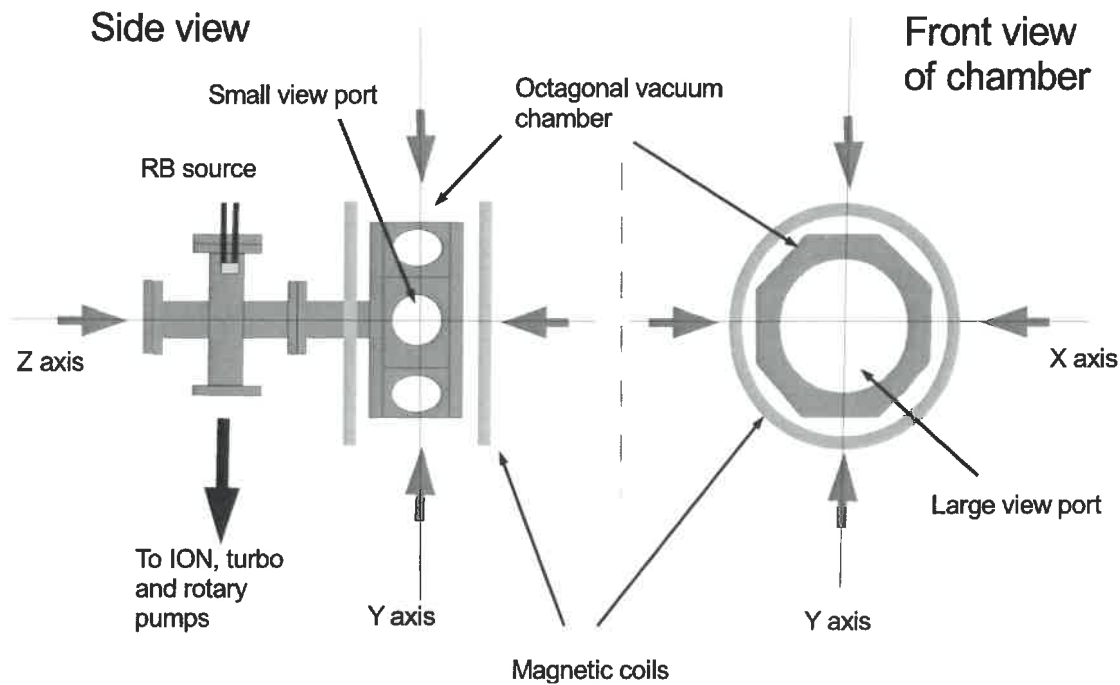


Figure 3. Schematic of the vacuum system. The system consists of an octagonal chamber having a number of view ports on the side and a large view port in front. Also shown in this figure are the counter propagating laser beams (red arrows) entering the chamber along the three axes. Positioned on either side of the chamber is the anti-Helmholtz magnetic coils.

are (a pair of)

passes through a half wave plate and then gets split three ways using polarizing beam splitter (PBS) and a 50/50 beam splitter. The half wave plate rotates the direction of linear polarization of the incoming laser beam and depending on the orientation it controls the amount of power that emerges in the arms of the PBS. One arm of the PBS produces the cooling beam on one of the axes. The other arm of the PBS goes to a 50/50 beam splitter which divides the power equally between the other cooling axis. The beams before entering the chamber are expanded using a set of lenses and passes through a quarter wave plate. The expanded beams have diameter of approximately 8 mm. Each beam is reflected back onto itself passing through a second quarter wave plate. The first quarter wave plate converts linear polarized light to circular polarized light. The second half wave plate changes the direction of circular polarization so that the overlapping beams in between the two quarter wave plates have counter rotating circular polarization. A repumping laser beam is combined with the cooling laser using a half wave plate and another PBS as shown.

The cooling and repumping laser frequencies are locked to the specific transition of Rubidium using a feedback system that consists of a saturated absorption setup (SAS) and servo-lock PID controller [3].

4. Results

The process to create cold atoms is quite involved: the two lasers first have to be locked to the correct frequency and this takes some trial and error before the lasers are locked. The Rb dispensers have to be turned on gradually and then the magnetic field is switched on. All of

Grammar hard to understand.

One says "divides the part equally between two axes, or one and the other". One can't divide power between one axis. Reward to be clearer.

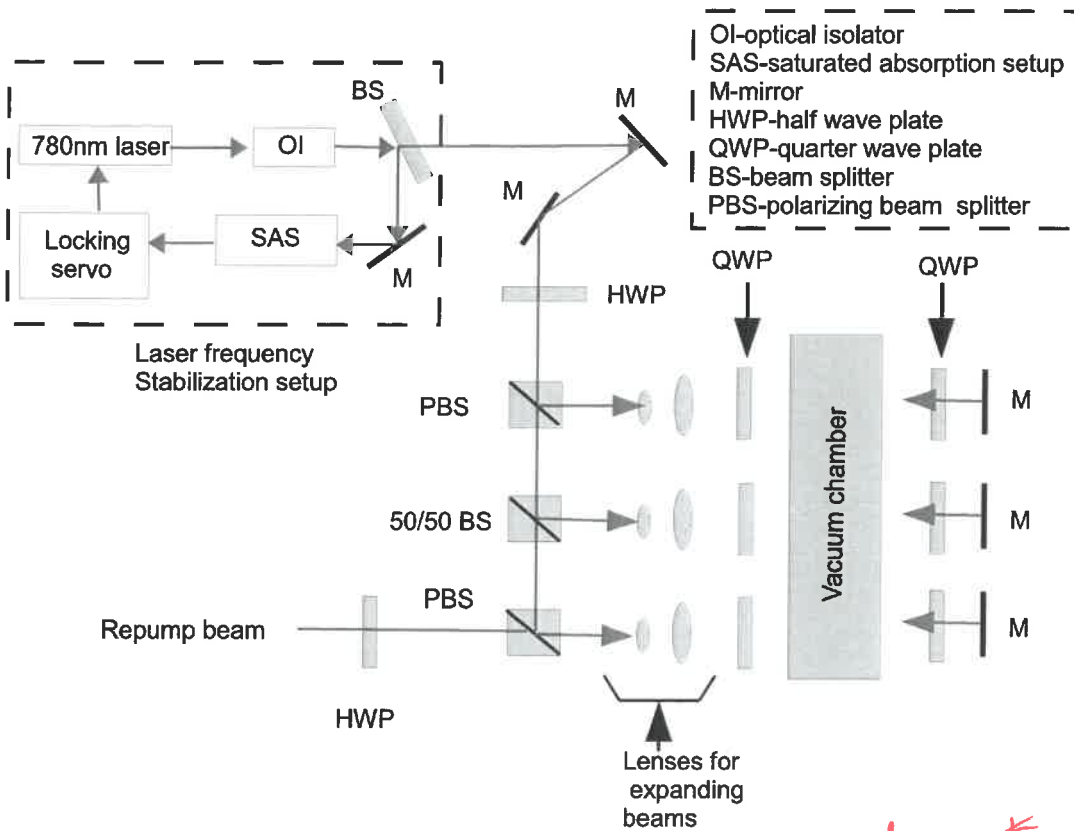


Figure 4. Optical setup.

these are done manually at the moment and usually takes two people to run and monitor all instruments at the same time. A cloud then forms within thirty seconds of everything being switched on. The images of the cloud are captured using monochrome CCD cameras. Figure 5 shows one of the images, looking through the large viewport in Figure 3.

Figure 6 shows a sequence of images spaced 200 ms apart showing growth of the cold atomic cloud (from left to right starting from top left) as soon as the magnetic field is turned on. These images are viewed via the side viewport in Figure 3. A 1 mm scale is also shown to give an idea of the cloud size. The size of the cloud is approximately 3 mm in diameter. These measurements were done using a magnetic field current of 4 A which gave a gradient at the centre of the trap of approximately 10 G/cm and the laser power on each beam entering the vacuum chamber was in the order of 3 mW.

To estimate the temperature of the cloud we have used a very simple method for now; the cooling laser is interrupted for a very short period and we monitor the integrated image of the cloud before and after the interruption of the beam. The temperature of the cloud can be related to the integrated cloud intensity before and after the beams are interrupted [6]. Our estimate of the temperature is $\approx 17\mu\text{K}$.

5. Summary and conclusion

In this paper we have described the construction and testing of a magneto-optical trap for laser cooling of rubidium atoms. The overall performance of the trap was analysed and a cloud of cold ^{87}Rb atoms was created having an approximate diameter of 3 mm and a temperature of around $17\mu\text{K}$. In addition ^{85}Rb was also cooled and trapped, although results of these were not shown.

They don't mention it.

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Not referred in text.

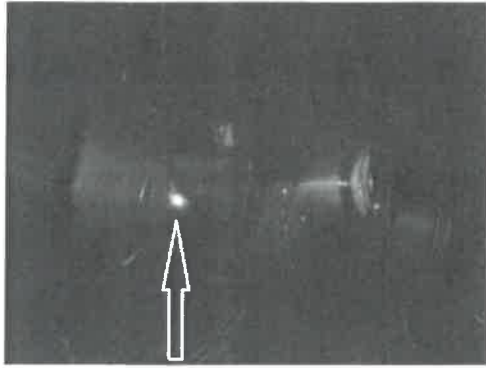


Figure 5. Image of the cloud viewed through the large viewport in Figure 3. The arrow points to the cloud.

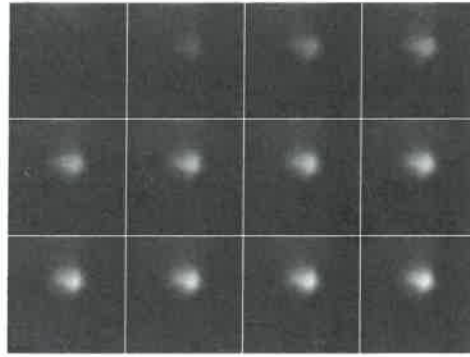


Figure 6. Sequence of images spaced 200 ms apart of the cloud showing growth from the time the system is activated.

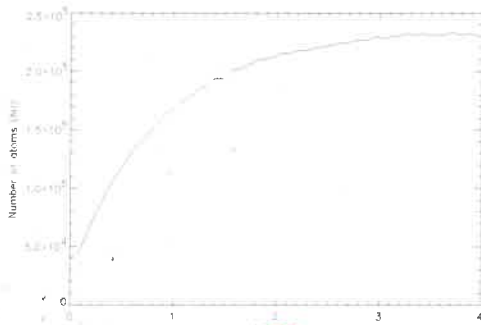


Figure 7. Integrated image intensity of the cloud as a function of time showing growth of the cloud of cold atoms from the time the system is started.

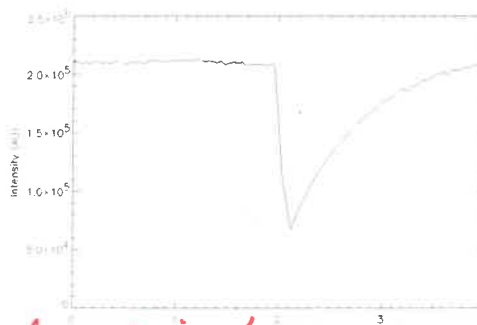


Figure 8. Integrated image intensity of the cloud as a function of time showing cloud growth after lasers are interrupted for a short duration.

Not referred in text.

References

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- [3] MacAdam K B Steinbach A and Wieman C 1992 *Am. J. Phys.* **60** (12) 1098-1111
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- [6] Arora P, Swatilekha Chowdhury S, Agarwal A, Pant K and Gupta A S 2011 *Indian J. Pure and Applied Phys.* **49** 590-5

Main objections are figures not referenced in text.